

SUV ROLLOVER TEST

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Abstract

The National Highway Traffic Safety Administration (NHTSA) approached NASA to evaluate vehicle rollover resistance using the High Capacity Centrifuge Facility. Testing was planned for six different sport utility vehicles. Previous methods for simulating the rollover conditions were considered to be not indicative of the true driving conditions. A more realistic gradual application of side loading could be achieved by using a centrifuge facility. A unique load measuring lower support system was designed to measure tire loading on the inboard tires and to indicate tire liftoff. This lower support system was designed to more closely emulate the actual rollover conditions. Additional design features were provided to mitigate potential safety hazards.

Test Objective

NASA and Mantech were approached by the National Highway Traffic Safety Administration (NHTSA) to evaluate the feasibility of measuring vehicle rollover resistance using our High Capacity Centrifuge (HCC) facility. They came to us since their previous test method was criticized by the automobile industry as not being realistic. The original test used was a sled type test where vehicles slid sideways along a track where they impacted with a curb type structure that caused the vehicle to tip. This posed several challenges since the curb impact was a suddenly applied load and vehicle response was difficult to measure. It was their opinion that gradual application of side loading was much more realistic to what would be experienced under actual driving conditions and instrumentation needed to be used to monitor the vehicle's response.

Testing was conducted on the High Capacity Centrifuge located in the Rotunda of building 15 at Goddard Space Flight Center, see Figure 1 below. The High Capacity Centrifuge was chosen because it could apply a controlled load at a slow rate and was capable of providing data and instrumentation to monitor a vehicle's response to the loading.

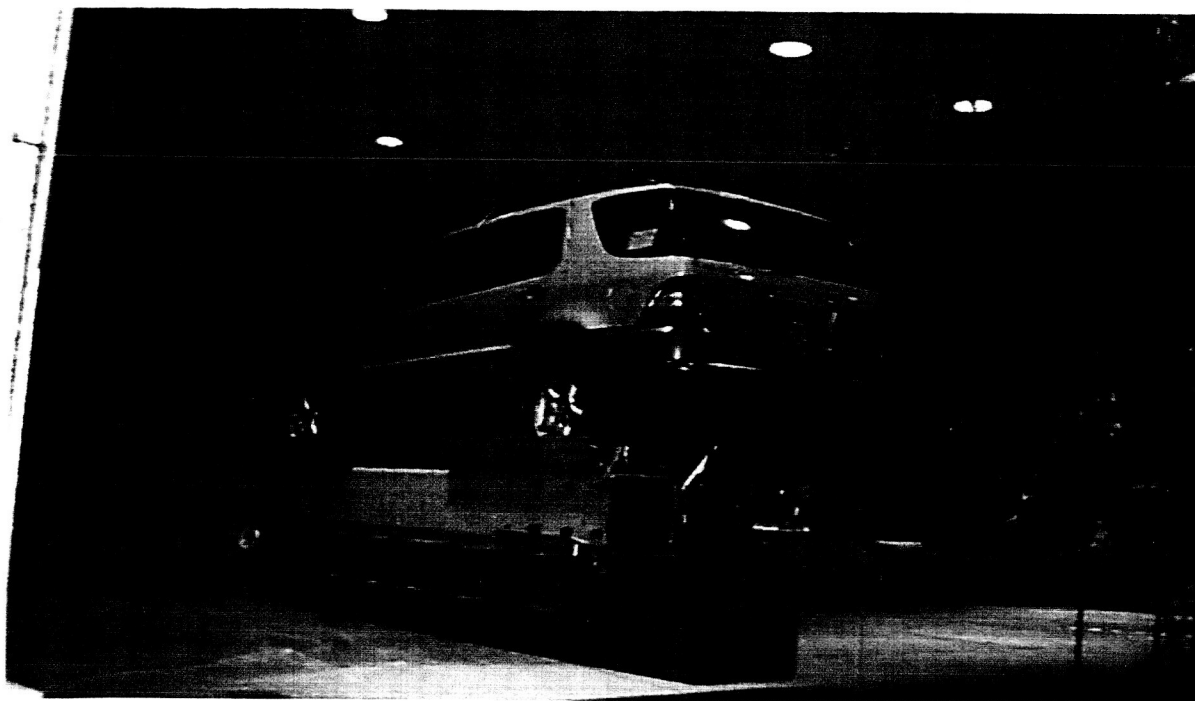


Figure 1. HCC Testing of an SUV at NASA Goddard Space Flight Center

This capability facilitated measuring the exact G load when tire liftoff occurs. A vehicle's dynamic response effects the rollover phenomenon and is difficult to predict and accommodate for in a sled type test. A centrifuge test accounts for the suspension system's dynamic movement during testing. Tire traction is another feature that can be realistically represented in the centrifuge test and is not simulated by the sled tests. The objective of the HCC tests was to demonstrate a repeatable method to determine the G level at which the two inboard (on the HCC) wheels of a vehicle raise off the ground.

The test fixture used on the HCC was designed to hold passenger cars, sports utility vehicles, pickup trucks or vans with weights up to 3175 kg (7000 lb), lengths up to 610 cm (240 inches), wheelbases 216 to 381 cm (85 to 150 inches) and track widths of 127 to 178 cm (50 to 70 inches). Load measuring plates were required under two wheels to measure vertical load as function of lateral acceleration. These plates were to be mounted so as to provide plus or minus 15.2 cm (6 inches) of low friction lateral movement.

The test was performed on a total of six cars. The first car (1993 Chevrolet Caprice) underwent extensive testing to determine the method to be used on the other cars. The remaining five cars underwent three or four test runs each, enough runs to obtain three repeatable runs.

The test method for each run was identical. The HCC was run to 3 RPM to verify the load balance. The rotational speed was then increased slowly with the next step set at a G value slightly above the predicted rollover value. The vehicle was to rise up and remained in the raised position for 1 minute, after which the HCC was gradually brought to a stop.

Description of Test Design

During the design phase, many challenges presented themselves. Facility capability, facility configuration, liftoff measurement features, vehicle suspension system movement, load measurement system/wheel interaction and vehicle restraint systems all posed different concerns.

Our first concerns included the load capacity and dynamic balance of the centrifuge and fitting the vehicles on the existing HCC test platform without major modifications. It was determined that load capacity and dynamic balance were not a problem since the HCC capacity is 2268 kg (5000 lb) at 30 G's and vehicle testing was estimated at 2268 kg (5000 lb) at 1 G. However, the existing platform diagonal supports ran through areas where the vehicles would be located and they would have to be replaced by shorter supports to provide sufficient platform space for vehicle testing (see Figure 2.). We did investigate whether SUV testing could be performed without diagonals altogether, but determined that this was not possible.

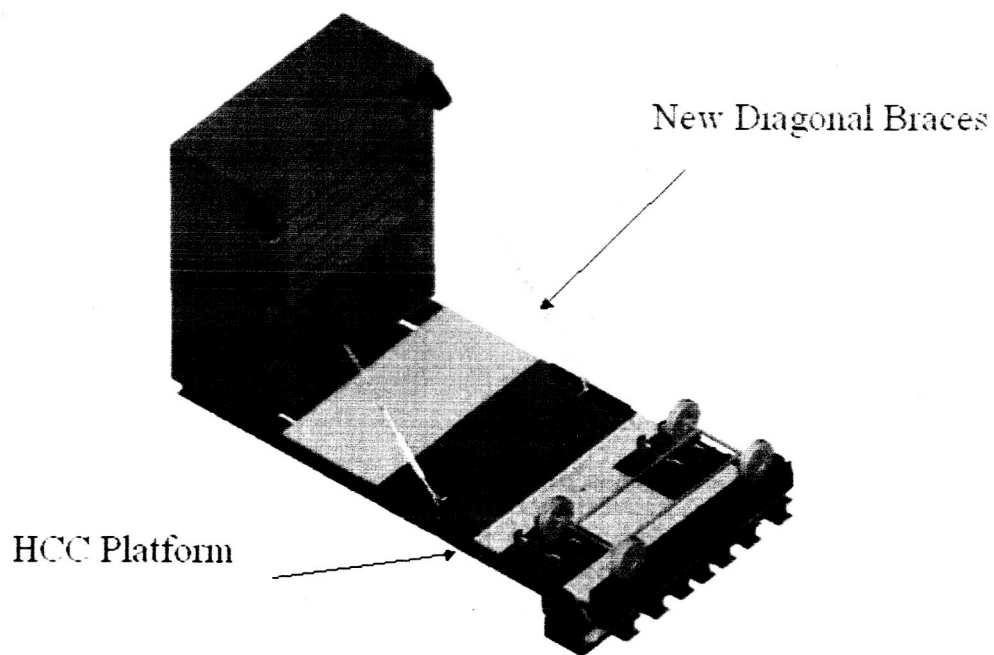


Figure 2. HCC Platform and new diagonal braces

A gradual and precise side-loading of the vehicle can be applied with the High Capacity Centrifuge at GSFC. The test radius of this centrifuge is 20.4m (67 feet). This large radius of curvature provides for a uniform acceleration across the profile of each vehicle. The HCC facility can be controlled to 1/100th of an RPM.

The NHTSA desired to know the exact point that the two inboard vehicle wheels lose contact with the road surface. This was accomplished by designing three pancake-type load cells positioned under each landing surface to precisely monitor vehicle lift versus applied G loading.

Two additional design considerations presented themselves early in the fixturing design process. The first consideration was that the load measuring system needed to follow the wheels such that the system was below the wheel's landing points after liftoff. This feature was needed since six different vehicles were planned for this testing with six different suspension systems. The customer preferred that the load measuring system did not adversely affect the test and impart any side loads onto the wheels in order to closely replicate the actual road conditions in service. Since the test needed to allow the vehicle to tip up 20 degrees off of horizontal, the load measuring system needed to follow the wheel as it shifted outward based on the stiffness of the various suspension systems (see Figure 3 below).

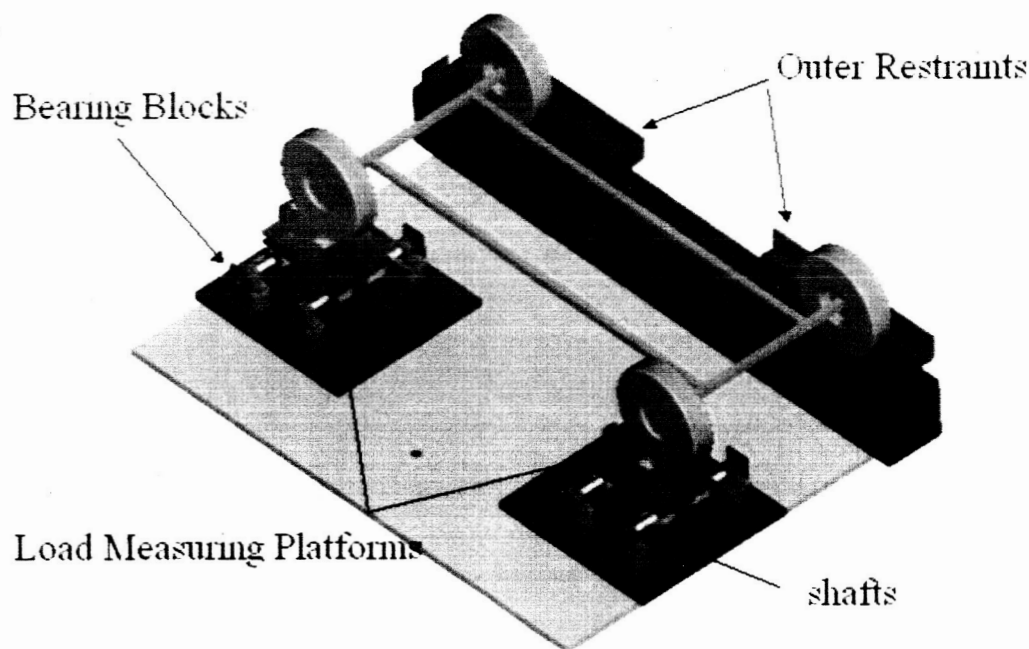


Figure 3. Load Measuring Platforms and Mechanical Slides

Since each load measuring system weighed in excess of 54.4 kg (120 lb), it was necessary to restrain the sliding load measuring system to prevent the system from moving relative to the vehicle tire. For the vehicle to "land" back on the load measuring system after tipping up 20 degrees, it was necessary that each load measuring system be restrained from excessive motion once vehicle liftoff had occurred. This would prevent the load measuring system from initiating a wheel liftoff prior to a natural liftoff caused by lateral acceleration.

The vehicle's wheels were permitted to move outward during testing since the load measuring systems were mounted on two steel slider shafts. The load measuring system was restrained with springs and bungee cords to prevent relative motion between the tires and the load measuring system. The movement of the tires during side loading was not well known by NHTSA since each vehicle had a different suspension system design. Movement was found to be significant under actual test conditions.

Another specially designed test fixture feature was to allow for this significant movement during testing. This was accomplished by allowing the load measuring system to slide on two horizontal shafts with bearings. Six inches of travel was provided on both sides of each load measurement platform to allow for motion by the suspension systems.

In order to duplicate actual road tire interaction, the inertial effects of the load measuring system needed to be minimized. In other words, the entire measuring and sliding support system needed to be extremely lightweight. Since the road surface does not move sideways relative to the tire, a spring system was designed to restrain the load measuring system. Each landing pad had four springs that would prevent the load measuring system from moving outward under the tire due to inertial G loading (see Figure 4.). This prevented the load measuring system from "helping" the tire liftoff.

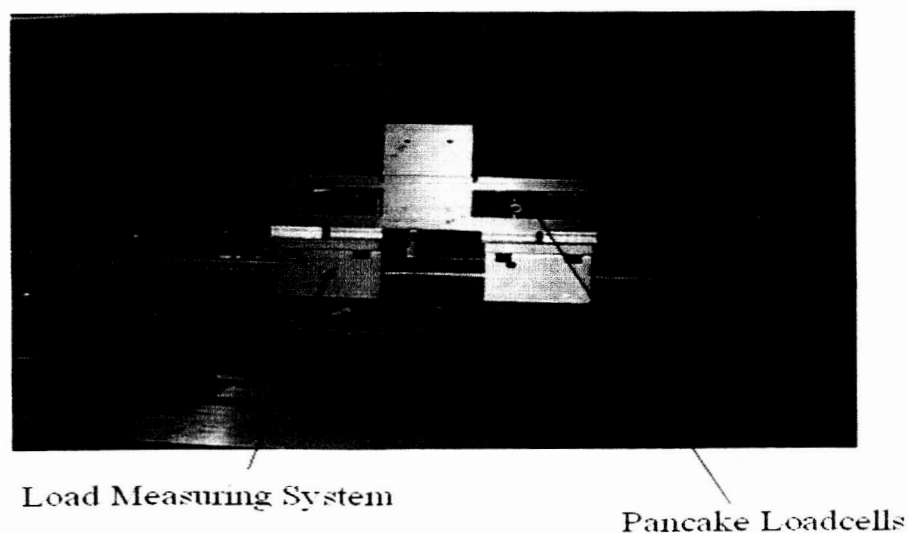


Figure 4. Load Measuring System and Retention Springs

Since each test vehicle had a different weight, four spring constants were chosen to react the 54.4 kg (120 lb) weight of the load measuring system. These springs were used to counteract the outward inertial movement of the load measuring system.

Next, restraints were designed to secure the vehicle to the test platform. Most centrifuge test payloads are securely bolted down to the platform. However, the NHTSA test plan calls for allowing each vehicle to raise 20 degrees off of horizontal. This requirement precludes a rigid connection to the HCC platform. Several passive restraint systems were designed to prevent the vehicles from rolling forward or backward in the direction of spin and to prevent the vehicles from jumping the outer curb and rolling off the end of the test platform. NHTSA supplied a standard curb feature that we incorporated as the outboard tire stop. For safety, an additional outboard hard stop was designed just in case the tires could not be retrained using the inner supplied curb feature.

A restraint system was devised which allowed tipping to the specified angle and prevented outward and tangential motion of the vehicle during testing. This system consisted of positive stops by way of a curb like structure for outward motion and tangential stops to prevent rolling motion due to HCC acceleration. Furthermore the HCC acceleration was kept very low at about 0.03 m/sec sq (0.1 ft/sec sq) or 0.003 G's.

Also, a system of nylon straps was used to secure the vehicle's frame to the HCC platform and to the main support structure while providing sufficient slack to allow the vehicle to tip to the desired angle. To prevent loss of vehicle during test, two passive restraint systems were designed to perform this testing on the HCC. One strap system restrained the vehicle at the upper body frame (between the front and back side windows) and at the inboard wheel lugs to the HCC weight bucket and the other strap system restrained the lower chassis to the HCC platform. Nylon straps were positioned at two locations under the vehicle chassis, at the outboard side and the inboard side that rotated up 20 degrees (see Figure 5 below).

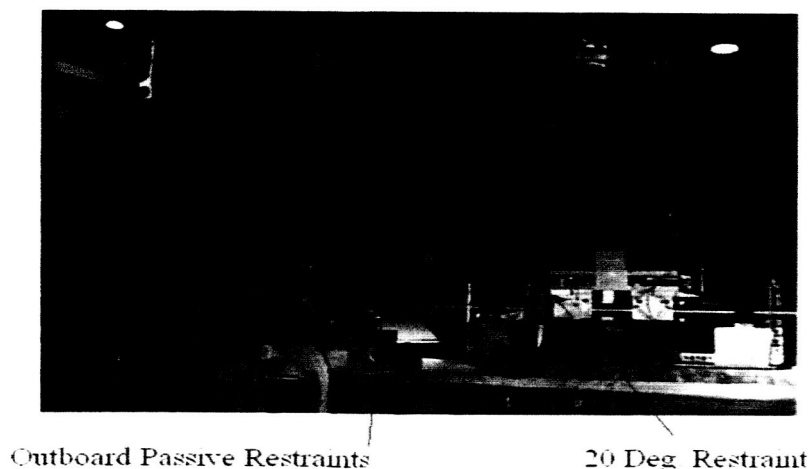


Figure 5. Load Measuring System and Passive Restraints

All fixturing components were designed with a factor of safety of 3.0 on material yield strength. Several restraint systems were designed for safety and redundancy.

Inboard wheels were instrumented to provide unloading data prior to vehicle tipping. The two inboard wheel landing pads were instrumented with three pan-cake load cells each to precisely monitor vehicle lift versus applied G-loading. The exact point at which the wheel lost contact with the road was a primary requirement by the customer.

A feature added later in the design cycle was to measure the load to restrain the vehicle once lift had already occurred. This was accomplished by attaching the restraint sling to the upper plate of the load measuring system. Once liftoff was achieved the restraint force was measured by the load measuring system as the car was held at 20 degree inclination.

The support system under the wheels was adjustable to accommodate six different wheel-base and wheel tracking schemes. This flexibility feature allowed for the movement of the load measurement base plates at three bolt down locations on the HCC platform.

Initially (during Caprice testing), instrumentation consisted of two accelerometers, a voltage channel to monitor arm speed, two limit switches (one on each platform to determine when the tire lifted off), and two load monitoring platforms. There were also six LVDTs, one of each of the two load platforms monitoring in/out movement of the platforms, and four along the centerline of the vehicles monitoring up/down motion of the vehicles.

Data analysis following the initial run of the Caprice showed that the voltage data obtained to determine the RPM of the arm was not precise enough for the customer's needs. Therefore, the accelerometers were used to determine all G levels for the test. A 1 G "flip-flop" to 2 decimal places was used to calibrate the accelerometers before each day's testing.

All data was acquired using a VXI base data acquisition system. The system has a capability of 160 channels. The data is multiplexed on board the HCC and transferred to the user interface using HP-IB extenders through a pair of slip rings located at the center of the HCC. During all testing, data was acquired at 15 samples/second/channel.

The following instrumentation was used:

Accelerometers: Two accelerometers were used, one measuring lateral acceleration of the vehicle (the direction which would result in tipover of the vehicle) and one measuring tangential acceleration (longitudinal axis of the vehicle). Both accelerometers measured to within 0.01 G. The lateral accelerometers measured the G force on the vehicle while the tangential accel measured zero throughout the tests, indicating that there was no forward or backward movement of the vehicle.

Load Weighing System: There were two load weighing systems, one under each inboard wheel of the vehicle. Each system consisted of three load cells summed to provide one output signal.

String Potentiometers: Six string pots were used for testing. Four, positioned approximately on the centerline of the vehicle, measured vertical displacement, i.e. sensed the vehicle lifting off the HCC platform. The remaining two measured lateral movement of the weighing systems.

Limit Switches: There were two limit switches, one in the center of each weighing system upper plate to determine when the tire no longer contacted the plate.

Summary of Test Results

The following vehicles were tested (in test order).

Table 1. Vehicle Testing Sequence

Vehicle	# of Runs
1993 Chevrolet Caprice	12
1998 Plymouth Voyager	4
1999 Mercedes Benz ML320	4
2001 Ford Escape	4
2001 Toyota 4Runner	3
2001 Chevrolet Blazer	4

NHTSA had calculated G levels at which vehicle roll up would occur. One or two tenths of a G (0.1 – 0.2) was added to that value and entered as the 100 percent full scale level for the test. For each test run, the HCC would first be run to 3 RPM. For the initial run on a vehicle, the centrifuge load balance would be checked at this point. For subsequent runs, the HCC would briefly stop acceleration at 3 RPM, since centrifuge safety requirements do not permit a direct increase to test level (approx 6.5 to 7.5 RPM). Following the 3 RPM hold, the HCC speed would slowly increase to the preset test level. Once the car lifted, that rotational speed would be held for 1 minute before stopping the HCC. After each test run, a thorough inspection of the vehicle and facility would be performed to see if the vehicle had shifted on the weighing system, if there was any damage to any instrumentation or if any other work was required prior to the next test run.

After the initial testing on the Caprice was completed, NHTSA determined that load platform data, and not the activation of the two limit switches, was an accurate means of determining vehicle lift off. Adjustment of the limit switches to activate at just the right location proved nearly impossible. These switches were not used following the first one of two test runs. The moment of liftoff was determined using the weighing system

output. Liftoff was achieved at the point where the load stopped changing. Therefore, the limit switch data was not used on subsequent vehicles, although the data was taken throughout the test program.

The setup detail that required the most iteration to optimize was the chain length attaching the tire lugs to the weighing platforms and a method to keep the chains from being caught under the tire when the vehicle settled back onto the platforms. The problems were ultimately resolved by determining the chain length difference that would be required by measuring the lug height differences when the vehicles were first hoisted onto the HCC. Tying the chain to the HCC diagonals using a bungee cord and a length of parachute cord solved the problem of the chains being caught under the tire.

Prior to the beginning of testing, NHTSA requested that the rate of increase of the HCC speed be reduced. The control system was modified such that the HCC speed increased at a rate $1/5$ that of a normal spacecraft test. The rate of decrease was not changed.

Following several tests on the initial vehicle to optimize the setup to be used for all subsequent testing, consistent liftoff values were obtained for each vehicle. Additionally, the values obtained were generally in agreement with calculated values provided by NHTSA. Rollover G loads were repeatable for each vehicle and values of 1.05 G's to 1.4 G's were measured.